Ocean Data Assimilation into the GEOS-5 Coupled Model with GMAO's ODAS-2

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Project Goal: The goal of this project is to develop and test the second generation of the GMAO's ocean data assimilation system (ODAS-2), a fully model-independent system, implemented within the GEOS-5 modeling system under the Earth system Modeling Framework (ESMF). One particular focus in the system validation has been the assimilation of remotely sensed sea surface height observations.

Project Description: Data assimilation refers to the process of using a numerical model to interpolate in space and time between sparse and inexact observations. Under certain reasonable assumptions, the Kalman filter can calculate the optimal weights with which to weigh the estimates of the state of a dynamical system (in our case the climate system) provided on the one hand by the model and on the other by the observations in order to arrive at the optimal state estimate. However, the Kalman filter is prohibitively expensive to implement for present-day climate models because it requires the propagation of the model background-error covariance matrix. For example, in the current implementation of the GMAO coupled model, the background-error covariance matrix of the ocean component alone has close to 10^{15} elements. Nevertheless, a statistical estimation approach known as the ensemble Kalman filter (EnKF) provides an attractive alternative to the Kalman filter by substituting the time propagation of the background-error covariances with a relatively small number of model integrations.

The GMAO has pioneered the application of the EnKF to complex numerical models of the ocean circulation. Our second-generation system (ODAS-2) has greatly improved over ODAS-1, the first-generation system developed for the Poseidon 4 ocean model (Keppenne et al., 2005). ODAS-2 can be used either in ocean only integrations or in coupled model experiments with any ESMF compatible ocean and atmospheric model. The current implementation uses the MOM4 ocean model. When ODAS-2 is applied in the context of the GEOS-5 coupled atmosphere-ocean model, the atmospheric model component is constrained by replaying the GMAO atmospheric analysis. Because the dominant timescales of the atmospheric circulation are much shorter than those of most ocean processes of interest, the replay procedure is approximately equivalent to assimilating ocean and atmospheric observations in the same experiment, while being substantially more economical than fully coupled ocean-atmosphere assimilation.

The complexity of the numerical models used restricts the number of model copies that can be run concurrently on even the most powerful supercomputers. As a result, the analysis has very few degrees of freedom (as many as the ensemble size) while the numerical model has $O(10^7\text{-}10^8)$ degrees of freedom. ODAS-2 addresses problems associated with limited ensemble size by combining error-covariance information from four sources: an ensemble of model trajectories, past states (lagged instances) along those model trajectories, a static ensemble of error empirical orthogonal functions and analytically formulated functional covariances. The first three covariance-information sources are multivariate (i.e., they can be used to update model variables other than what is being observed such as temperature and salt when sea level height is observed) while the fourth is univariate. In addition ODAS-2 also combines the EnKF analysis step with a particle-filter pre-analysis, resulting in more realistic ocean state estimates than the EnKF alone can provide.

Another way to address the degrees-of-freedom limitation is by localizing the analysis procedure. In doing so, a multitude of low-dimensional problems is solved rather than one global high-dimensional problem. This approach is commonly used in data assimilation and involves a substantial amount of guesswork in determining the size of the localization regions. ODAS-2 introduces a completely adaptive algorithm to optimally calculate the localization parameters involved in the processing of each observation. The adaptive algorithm also produces an objective estimate of the representation error of each observation, thereby eliminating some guesswork.

Results: Before the Argo era, relatively few observations of the ocean subsurface were available, hence the accuracy of the ocean state estimates during that period is highly dependent on how well the surface observations, especially remotely-sensed sea surface height measurements, can be utilized to infer information about the subsurface. Cross-validation against temperature, salinity and current profiles from fixed buoys and other *in situ* measurement sources shows that the new algorithms used in ODAS-2 have resulted in performance breakthroughs over ODAS-1 as illustrated in Figure 1. Figure 1 shows the improvements in temperature and salinity estimates in ODAS-2 when only sea level height anomalies are assimilated over those from a coupled model run without data assimilation. The improvement is measured by the differences in root mean square difference between the analysis or model estimate and independent (i.e., not assimilated) Argo profiles, integrated vertically through the water column from the surface to 2000m. Warm (cold) colors correspond to areas where the assimilation results in the model field that is closer to (further away from) the Argo temperature or salinity profiles. White areas on the pictures correspond to places where no Argo profiles are available for cross-validation.

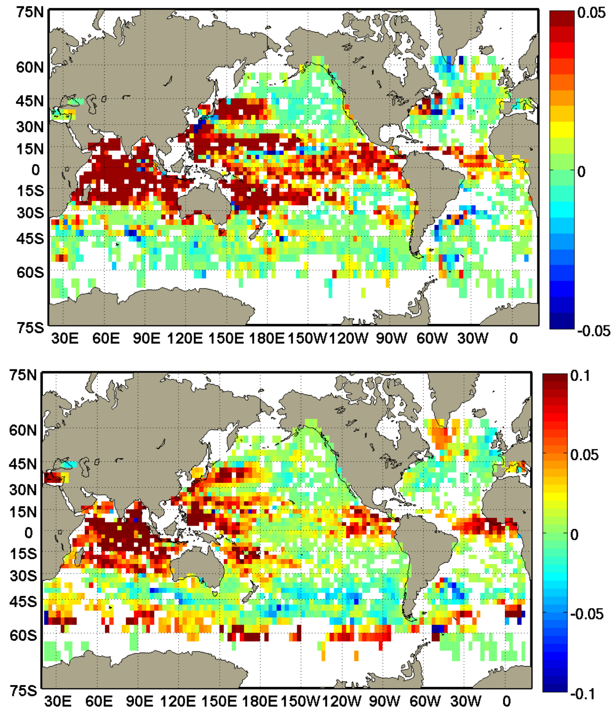

Figure 1: (a) *Relative closeness (relative to a control integration without data assimilation) to independent, not-assimilated Argo temperature profiles (integrated vertically) when sea level height anomalies are assimilated. (b) same as (a) for Argo salinity profiles. (See text).*

References

Keppenne, C.L., M.M. Rienecker, N.P. Kurkowski and D.D. Adamec, 2005: Ensemble Kalman filter assimilation of altimeter and temperature data with bias correction and application to seasonal prediction, *Nonlinear Processes in Geophysics*, **12**, 491-503.

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